WRDC-TR-89-3110

CORRELATION/VALIDATION OF FINITE ELEMENT CODE ANALYSES FOR VIBRATION ASSESSMENT OF AVIONIC EQUIPMENT

AD-A220 393

Amar Bhungalia and George Kurylowich

Environmental Control Branch

Vehicle Subsystems Division

December 1989

Final Report for Period March 1985 - September 1989

Approved for public release; distribution unlimited.

FLIGHT DYNAMICS LABORATORY
WRIGHT RESEARCH AND DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6553

90 04

NOTICE

WHEN GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY GOVERNMENT-RELATED PROCUREMENT, THE UNITED STATES GOVERNMENT INCURS NO RESPONSIBILITY OR ANY OBLIGATION WHATSOEVER. THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA, IS NOT TO BE REGARDED BY IMPLICATION, OR OTHERWISE IN ANY MANNER CONSTRUED, AS LICENSING THE HOLDER, OR ANY OTHER PERSON OR CORPORATION; OR AS CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

AMARSHI A. BHUNGALIA
Project Engineer
Environmental Reliability Group
Environmental Control Branch

GEORGE KURYLOWICH, Ph.D
Technical Manager
Environmental Reliability Group
Environmental Control Branch

FOR THE COMMANDER

RICHARD E. COLCLOUGH, JR.
Chief
Vehicle Subsystems Division

IF YOUR ADDRESS HAS CHANGED, IF YOU WISH TO BE REMOVED FROM OUR MAILING LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION PLEASE NOTIFY WRDC/FIVEC, WRIGHT-PATTERSON AFB, OH 45433-6553 TO HELP MAINTAIN A CURRENT MAILING LIST.

COPIES OF THIS REPORT SHOULD NOT BE RETURNED UNLESS RETURN IS REQUIRED BY SECURITY CONSIDERATIONS, CONTRACTUAL OBLIGATIONS, OR NOTICE ON A SPECIFIC DOCUMENT.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): WRDC-TR-89-3110

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Flight Dynamics Laboratory, Wright Research Dev. Ctr.

6b. OFFICE SYMBOL *(If applicable)*: WRDC/FIVE

6c. ADDRESS *(City, State, and ZIP Code)*: Wright-Patterson Air Force Base Ohio 45433-6553

7a. NAME OF MONITORING ORGANIZATION:

7b. ADDRESS *(City, State, and ZIP Code)*:

8a. NAME OF FUNDING / SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL *(If applicable)*:

8c. ADDRESS *(City, State, and ZIP Code)*:

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62201F	2402	04	53

11. TITLE *(Include Security Classification)*: Correlation/Validation of Finite Element Code Analyses for Vibration Assessment of Avionic Equipment

12. PERSONAL AUTHOR(S): Bhungalia, Amar and Kurylowich, George

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM Mar 85 TO Sep 89

14. DATE OF REPORT *(Year, Month, Day)*: 89/12/31

15. PAGE COUNT: 37

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: Avionics Reliability, Environmental Reliability, Military Aircraft, Dynamic Analysis Validation, Finite Element Predictions.

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Avionics Environmental Reliability is a major issue for present and future military aircrafts. The printed wiring boards are getting more and more populated with electronic components because of very complex avionics requirements with limited space available in the avionic bay. With this limited available space, we are forced to design the printed wiring board with very densely populated electronic components. It appears that this kind of condition can create structural integrity problems for avionics in military aircrafts. It has been determined that vibration and thermal environments are major problems in military avionics, and these environments cause more than half avionics failures. There is a need to evaluate a design before we approve go ahead on production of these complex avionics boxes. WRDC/FIVE has started to develop a computer capability to predict avionics reliability prior to production, so that the design can be changed if it does not meet the Air Force requirements. WRDC/FIVE has selected/developed a finite element program which will allow avionics reliability prediction. The Numerically Integrated elements for System Analysis (NISA) software was

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Bhungalia, Amar

22b. TELEPHONE *(Include Area Code)*: (513) 255-3021

22c. OFFICE SYMBOL: WRDC/FIVE

selected to accomplish this task. In May 1984, the Environmental Control Branch (WRDC/FIVE) started In-House effort to validate vibration prediction using NISA and test data acquired from laboratory test, with similar boundary conditions. This report contains the results of validation of predictions by showing comparisons with test data.

FOREWORD

This report was prepared by personnel of the Vehicle Subsystems Division, Flight Dynamics Laboratory (WRDC/FIV). The report contains the results of an in-house research effort wherein, tests on various types of Printed Circuit Boards (PCB) were performed to collect vibration test data. The testing was conducted by the Vibration Field Instrumentation and Acquisition Group, Structural Dynamics Branch (WRDC/FIBG) with Lt. A. D. Swanson as the test engineer. The finite element code, "Numerically Integrated Elements for Systems Analysis" (NISA), was utilized to form the correlations between the analysis and test data. The finite element code, "NAsa STRuctral ANalysis" (NASTRAN) was also used to provide NISA and NASTRAN correlations.

This work was conducted from March 1985 to September 1989 under work unit No. 24020453. This effort was conducted as a start to an in-house effort directed to provide a validated Computerized Avionic Design (CAD) tool. The objective is to develop an assessment capability useable by the avionic procurement community in purchasing avionics for DoD weaponry.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

SECTION - 1

PROGRAM INTRODUCTION AND BACKGROUND

1.1 PROGRAM INTRODUCTION

Electronic enclosures in an aircraft go through many different forms of vibrations over wide frequency ranges and acceleration levels. These acceleration levels have induced very high stresses in electronic components which can cause the components to fail. Vibration is one of the major factors which affects avionic reliability; that is, it is an unavoidable condition in military aircraft and missiles. Therefore, the avionic designer has to design electronic boxes to withstand these vibration levels. Many of the vibration problems can be minimized by avoiding coincident resonances which can magnify acceleration G forces very rapidly. The resonances of the printed circuit board can be easily evaluated by utilizing finite element analysis methods; and hence, the coincident resonances can be avoided during the Printed Circuit Board (PCB) preliminary design and development stage. This can be accomplished by redesigning the PCB in many different ways such as adding additional stiffness to the PCB board and rearranging the ply lay-up of composite PCBs. This would add overall stiffness in the PCB and the resonance frequencies would be higher. The higher resonance frequency would have lower deformation in the PCB. This decreases the effect of acceleration G forces on the electronic components and hence must decrease the induced stress in component lead wires which would improve the reliability of electronic components.

1.2 PROGRAM BACKGROUND

During the acceptance of avionic designs, the Air Force program office personnel are under pressure to rapidly assess and approve the design submitted by a defense contractor. Many independent factors must be considered to determine the adequacy of the design. One of these factors is the suitability of the design for the anticipated aircraft environment. It is observed from study [1] that 14% of the avionic failures are due to the vibration environment as compared to the total avionic equipment field failure distribution. It is also shown that the environmental factors are responsible for as much as 52% of all avionic failures, reference is made to Figure 1. It is of note that the data gathered and reduced to form the results given in Figure 1 were an initial result of a 1971 conducted study. It is further of interest to note that the Figure 1 data also reflects 1984 data reviewed by WRDC/FIVE during 1985. This was found from reliability data from all Air Force sources contacted. The strong contribution of environmental effects to avionic failures reflects the importance of being able to evaluate avionic designs for environmental suitability as early as possible in the design cycle of avionic equipment. WRDC/FIVE started an in-house/contractual effort in 1984 to develop a Computer-Aided-Engineering (CAE) process which would allow an avionic designer or program office to form assessments of the worth of avionics by analysis of the electronic design for its temperature and vibration environments. Stresses on individual components will be determined through CAE. In addition, use of the CAE process is to be used to identify unacceptably large deformations between the Printed Circuit Board (PCB) and the electronic component(s) so as to identify flaws in the overall design as predicted by the CAE capability presented. WRDC/FIVE objectives and thrusts include assessment of thermal-cyclic impacts upon the stress-strain and failure considerations associated with avionics. The stress-strain aspects when induced by vibration and thermal inputs is accounted for in the CAE capability described above. The presentation given herein addresses correlations of test and analysis as related to vibration only. The issue of thermal cyclic impacts upon avionics, and for that matter, the impact of combined stresses and strains as caused by the combination of a real-world thermal/vibration aircraft-induced environment is beyond the scope of this study.

SECTION - 2

PROGRAM OBJECTIVE, APPROACH, AND TEST PROCEDURE

2.1 OBJECTIVE OF THE EFFORT (TECHNICAL AND EXPERIMENTAL)

The objective of the overall effort is to support Air Force program offices' selection of avionics for use in the Department of Defense (DoD). This support is provided by developing an evaluation criteria for selecting the "best" avionics by the appropriate DoD office. A computerized capability has been developed within WRDC/FIVEC. The objective of this effort is to validate the computerized capability for use by the appropriate DoD office. This technical report serves as part of the overall validation.

2.2 EFFORT APPROACH (TECHNICAL AND EXPERIMENTAL)

To accomplish the objective, the Numerically Integrated Elements for Structural Analysis (NISA) [2] and the NAsa STRuctural ANalysis (NASTRAN) [3], computer codes were used to predict vibrational resonant frequencies for several theoretically-described printed wiring boards. The NASTRAN computer code was selected to affect validation because it is well known, has been validated, and accepted in the structural community by government and private industry. Additionally, theoretical equations from relevant text [4, 5] were used to calculate resonant frequencies of interest herein. The correlation of both NISA, NASTRAN, and the theoretical equations from Reference 4 and 5 were performed and are discussed below.

The specimens for the test effort were selected to reflect general printed circuit board shapes and their associated boundary conditions. For general information to this effort, a typical avionic box or Line Replaceable Unit (LRU) is rectangular in shape and generally has a rectangular-thin printed circuit board installed with a connector at one edge and with two edges supported by spring guides or wedge clamps.

Theoretically defined boundary conditions were selected for simulation/duplication in the laboratory to keep fixture structures simple, while still being representative of the boundary conditions for a real PCB. Three types of boundary conditions were selected: fixed, simply-supported, and free-edged. These boundary conditions typify those currently exerted on printed circuit boards when mounted in Line Replaceable Units (LRU).

The program was divided into two phases. Phase I consisted of theoretically analyzing defined plates with no attached electronic components. This effort consisted of comparisons showing correlation of NISA/NASTRAN predictive capabilities. Phase II consisted of testing plates with attached electronic components.

This effort resulted in fabrication of representative "to-day" avionic boards, testing these boards in the laboratory, and correlating the results with analytical prediction.

2.2.1 PHASE 1 - THEORETICAL COMPARISONS (NO ATTACHED COMPONENTS)

Theoretical calculations and finite element predictions were compared for a 6.0 x 6.0 x 0.062 inch plate with seven different combinations of classically represented boundary conditions. The plates were theoretically represented as steel because this material is isotropic and its material properties are readily described.

2.2.2 PHASE 2 - CORRELATION OF TEST AND ANALYSIS (COMPONENTS ATTACHED)

Testing for vibrational resonance of sample avionic boards was conducted in the laboratory. The analytical capability used for analysis was the NISA finite element program, as modified by the government to provide: (1) Preprocessed digitized representations of a PCB equipped with electronic components; (2) Postprocessed algorithms that provide an estimate of the stress, strains, and resonances of the PCB; and (3) an estimate of the reliability associated with the PCB under the actual environment imposed. Figures 2 through 5 reflect the test fixture setup that was used in this validation effort. Figures 6 through 9 provide the description of the test specimens that were mounted in the fixtures. These figures also provide the locations of the electronic components on these specimens as well as the locations of the accelerometers used. The accelerometers provided the measure of the first five natural frequency modes for each of the specimens tested for purposes of comparison with analyses performed with the Finite Element Method (FEM) code NISA.

2.2.2.1 The electronic components mounted on the specimens described above consisted of capacitors, diodes, transistors, relays, and where the IC dips consisted of at least 14 pins. These components were representative of electronic items purchasable from "Radio Shack." All of these components weighed less than E^{-5} in terms of mass, in units of $lb/sec^2/in$. The accelerometers used during this test were even lighter than the components just described. Analysis indicated that the electronic components and accelerometers were representable as point mass depictions in the finite element analyses, as used herein. The copperclad plates were 6 x 6 x 0.066 inch, and were copper faced on both top and bottom to a depth of 0.003 inch. The middle core of these plated specimens consisted of fiberglass, 0.06 inch thick. These board samples with the electronic component geometrical locations noted are shown in Figures 6 through 9. No more than 10 electronic components were mounted on each of these boards tested. The locations for the accelerometers used in measuring the data needed to determine the first five resonant frequency modes for all of the boards tested are also shown in these figures. The seven different boundary condition/board configurations tested under controlled laboratory conditions were: (1) cantilever board copperclad and steel plate - one edge fixed and three edges free; (2) copperclad and steel plate - two opposite edges fixed and two edges free; (3) copperclad and steel plate - three edges fixed and one edge free; and (4) two opposite edges simply supported with Burcher Guides and one edge fixed by a printed circuit board connector. This last test setup reflects most appropriately the mounting conditions of a Printed Circuit Board (PCB) in a typical military Line Replaceable Unit (LRU). Reference is made to Figure 9.

2.3 TEST PROCEDURES

Four copper and three steel circuit boards were manufactured and tested as per descriptions provided above. Again, the Phase I effort described above was a theoretical exercise. Phase II was an experimental effort as PCBs were built and tested. All of the PCBs, used in the Phase II effort, were attached to a shaker armature with a 38.5-pound circular steel plate and ASTM A-36 steel mounting blocks (see Figures 2 through 5). The test data were reduced and recorded onto digital magnetic tape with the appropriate discretization parameters to provide a frequency resolution to match the discrete bands of the shaker input (4 Hz for flat random data and 1 Hz for the variable spectrum data).

A Raytheon 704 computer system was used to apply the gain-corrected transducer calibration, to insert data identification, and to reformat the digital tapes into a VAX computer format for further processing. A VAX-11/780 computer system, configured with an array processor and an electronic plotter, was used for the final analysis. The data were converted to the frequency domain using Fast Fourier Transform (FFT) techniques with the array processor. The amplitude spectra were then computed from the Fourier Transforms and the results were plotted in frequency versus Root Mean Square (RMS) acceleration. Sinusoidal and random vibration tests were performed during board tests with the following specifications. Each of the seven circuit boards was excited with both sine-sweep and random disturbances. The sine-sweep was performed from 18 to 1,719 Hz for the cantilevered and fixed-fixed copper and steel boards. For the triple-clamped and Burcher guides with PCB connector mounted boards, the sweep frequency evaluation ranged from 19 to 1,718 Hz. In all cases, the vibration level was a constant 1 grms. Two spectra were used for the random disturbance tests, one flat and one variable. The flat spectrum extended from 20 to 1500 Hz for a total of 1 grms.

The recorded data were analyzed by WRDC/FIBF and provided to WRDC/FIVE. The sine-sweep data records were analyzed by passing each channel through a frequency tracking filter and plotting the resulting amplitude on an X-Y plotter. For the random data, a preliminary analog analysis of selected channels was performed using an analog spectrum analyzer to determine the frequency limits of the data and digitizing parameters. During this analysis, the test data were compared with the no-signal and calibration data to establish noise floors and signal-to-noise ratios. Data from the selected test conditions were low-pass filtered at 2,000 Hz for the flat random data and 500 Hz for the variable spectrum data, and then digitized.

SECTION - 3

CORRELATION OF FINITE ELEMENT ANALYSIS AND TEST

FINITE ELEMENT ANALYSIS AND CORRELATION WITH TEST

Upon receipt of the preprocessor software in late 1986, an in-house effort was initiated to validate the NISA vibrational capability. The first effort undertaken as Phase I, described in Section 2.2 above, was to correlate the finite element model against exact solutions provided by Steinberg (4). In addition, this effort included use of the NASTRAN computer program for purposes of correlations with the results from the NISA program, and the results are shown in Figures 10 through 16. The purpose of the NASTRAN correlation effort was that NASTRAN, though difficult to use by a novice structural analyst, is widely accepted within government and industry as a structural stress analysis standard.

It is seen that the correlation for vibrational frequency, f_n, the vertical axis in cycles per second in these figures, is excellent between the exact theoretical solution, and the NISA and NASTRAN results for the first 5 modes of frequency, f_n, excitation. The exact solution for the first natural frequency mode, f_n, as taken from Reference 4 is shown in each of the figures as well as the type of boundary conditions imposed upon the plate edges. The board thickness was 0.062 inch and the material was steel, a well known isotropic material. The natural frequency modes 2 through 5 were obtained by multiplying the result for mode 1 by adjustment factors given in Reference 5 to reflect f_n modes 2 through 5 as a function of the number of free edges, supported edges, and fixed edges restraining the board. This procedure was applied for all modes above the first for the results shown in Figures 10 through 16. As indicated above, the correlation of the NISA and NASTRAN results with the exact solution is excellent with the correlations being within 2%.

NISA correlations were also performed on the electronic plate specimens that were fabricated and tested in the laboratory. See Section 2.3 where the test effort and specimens, that were fabricated to host 10 electronic components plus accelerometers are described in detail. The correlations between the test data and the NISA Finite Element Methods (FEM) capability are shown in Figures 17 through 22.

A sketch of the laboratory specimens tested, in relation to the boundary conditions imposed on the specimen, are shown in each of the figures given. These sketches can be used for easy reference to the discussions provided in Section 2.3. As seen in Figures 17 through 21, the correlation of analysis and test data was very good with the correlation between test and finite element analyses being within 5%. The greatest deviation was 15% for the 3rd natural frequency mode given in Figure 22.

A general review of the experimental data gathered during the test effort indicated that the measured linear displacement data perpendicular to the board (in inches) had significant errors associated with it. These data with unreasonably large errors were not reduced to engineering-useable information. The noise was due to either the magnetic tape recording equipment, the sensitivities of the measurement devices used to obtain the data, or due to the extraneous acoustical background noise that was not measured independently and that could not be filtered out so as to "back out" the necessary information. Unfortunately, the test capability as well as the instrumentation set up were taken apart after these experimental tests were conducted. That is, the tests were not redone. As a result, the test data for frequencies of the 4th and 5th modes in Figure 19 are not shown as well as the mode 3 and 5 frequencies in Figures 20 and 21, and the mode 5 frequency in Figure 22. The large non-resolvable scatter in the experimental data also precludes giving any correlation for the 3rd frequency mode in Figure 22.

SECTION - 4

CONCLUDING REMARKS AND RECOMMENDATIONS

The objective of this, and ongoing efforts within the military, is to support Air Force program office personnel in their selection of avionics for use in the Department of Defense (DoD). This support, as provided by WRDC/FIVE, culminates in developing a validated assessment tool that rapidly assesses the reliability of an avionic capability submitted by a contractor for procurement.

Analyses were performed using a Finite Element Modeling (FEM) capability developed under contract within WRDC/FIVE, to correlate with the results of analyses that were conducted using NASTRAN. The Printed Circuit Boards (PCB) represented consisted of rectangular plates reflecting electronic boards, restrained by simple boundary conditions and perturbed so as to excite the resonance frequencies. The correlation results as evaluated by NASTRAN and NISA was within 2% for the first five resonant frequencies excited.

Test data were obtained for the first five resonant frequencies of copper-clad circuit board stock plates simulating avionic boards, restrained by various boundary conditions. Ten electronic components were mounted on these boards with accelerometers mounted on the plates to measure frequencies. The correlation of the analysis developed by WRDC/FIVE with the test data gathered for the first five resonant frequencies was generally within 5%. The stiffness of the boards was very high compared to the electronic component stiffness. Therefore, each electronic component was considered as a point mass on the printed circuit board. As the size of the mounted electronic component becomes larger, the added stiffness on the PCB can become very critical. Additionally, one realizes that the mass of the component as a point mass for finite element analysis is a naive representation when an electronic component such as a large, heavy transformer is located on a small board, as an example. The definition of what is small or not needs further definition whithin the mathematical models presented herein.

It is recommended, therefore, that future testing within WRDC/FIVE include a well designed matrix of all test conditions definable reflecting all of the boundary conditions possible when a PCB board is restrained in an electronic box. This effort would be followed by an investigation to show the correlation between analysis and test. In this manner, the worth of the NISA capability can be defined, technology gaps identified, and additional algorithms needed to improve the accuracy of the prediction derived. The future test exploitation areas needed to be assessed are the effect of increased component size, mass, and stiffness in comparison to board dimensions, as well as structural mass and stiffness characteristic effects. This is needed to fully explore where components can be represented by a point mass and where a more detailed model is needed so as to retain good correlation between analysis prediction and test data.

REFERENCES

1. Dantowitz, A., Hirschberger G., and Pravidio, D., "Analysis of Aeronautical Equipment Environmental Failures," AFFDL-TR-71-32, 1971.

2. Kothawala K. S., Mathers M. D., Razzaque A., Ho P., El-Essawi M., "Numerically Integrated Elements for System Analysis User's Manual," 1883.

3. "The NAsa STRuctural ANalysis User's Manual," 1985.

4. Steinberg, D. S., "Vibration Analysis for Electronic Equipment," John Wiley & Sons, 1973.

5. Leissa A. W., "Vibration of Plates," National Aeronautical and Space Administration, NASA, 1969.

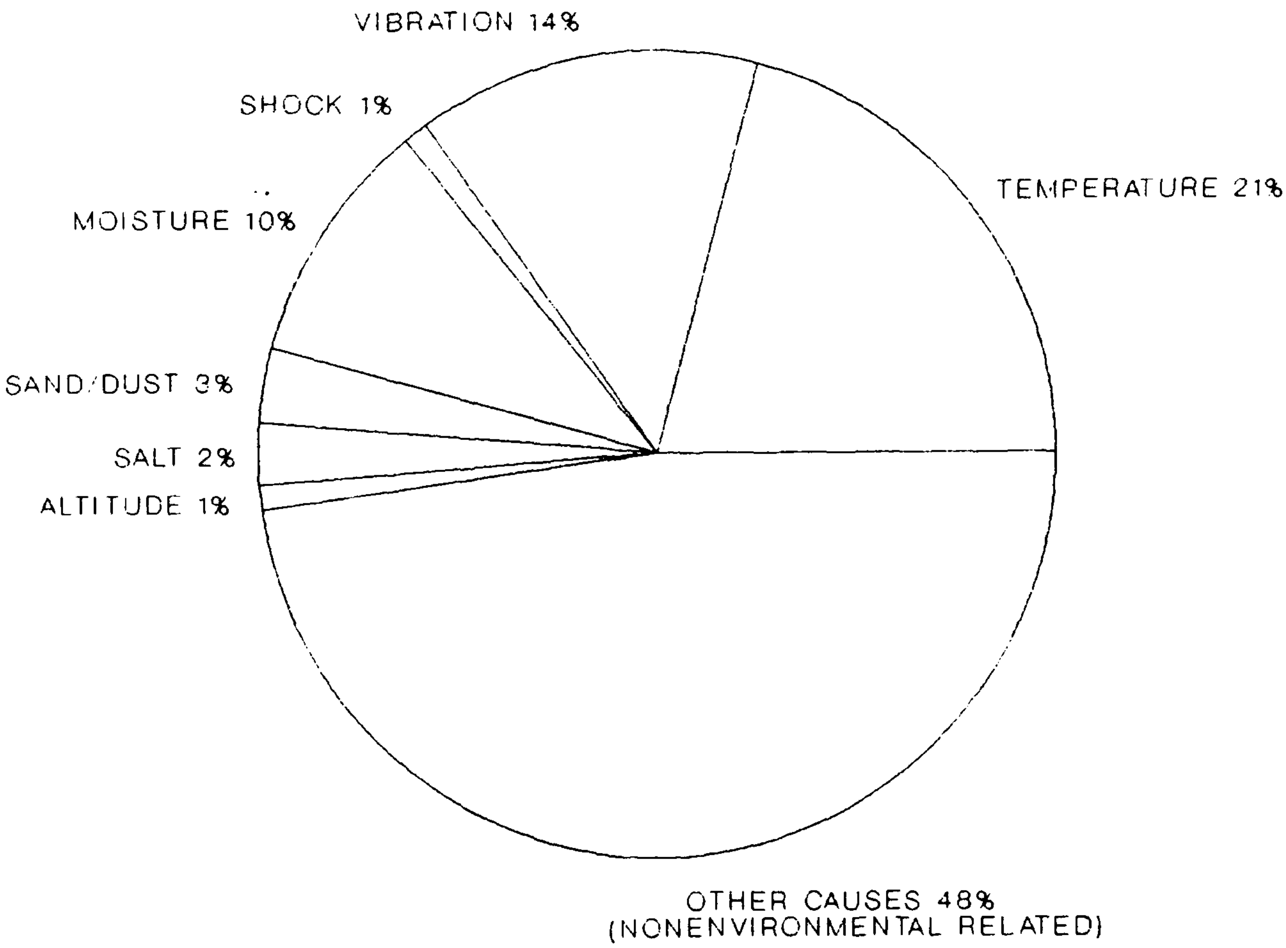


FIGURE 1 ESTIMATED AVIONIC EQUIPMENT FIELD FAILURE DISTRIBUTION (1971)

FIGURE 2 TEST SETUP FOR CANTILEVER PLATE BOUNDARY CONDITION

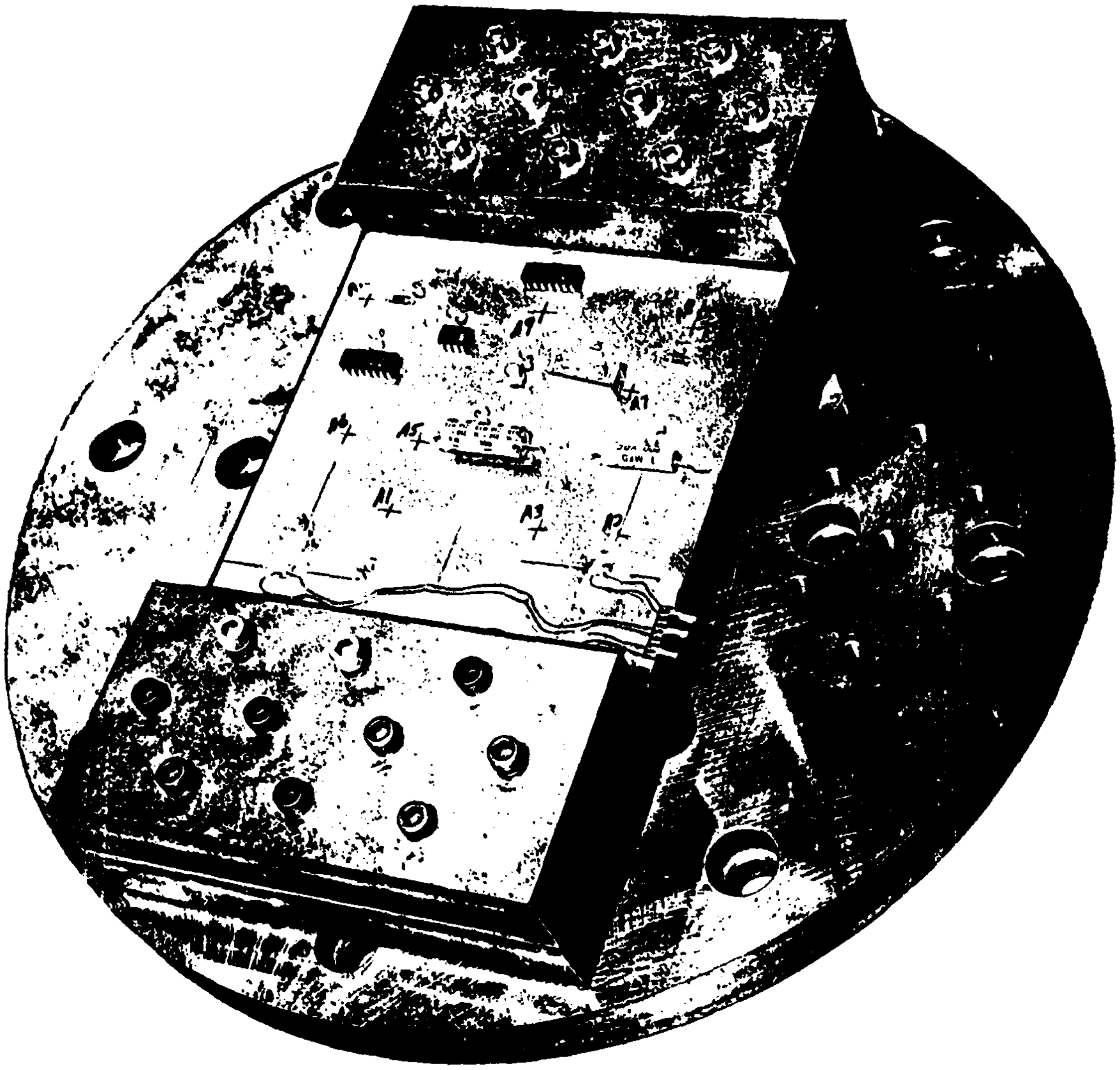


FIGURE 3 TEST SETUP FOR TWO EDGES FIXED BOUNDARY CONDITION

FIGURE 4 TEST SETUP FOR THREE EDGES FIXED BOUNDARY CONDITION

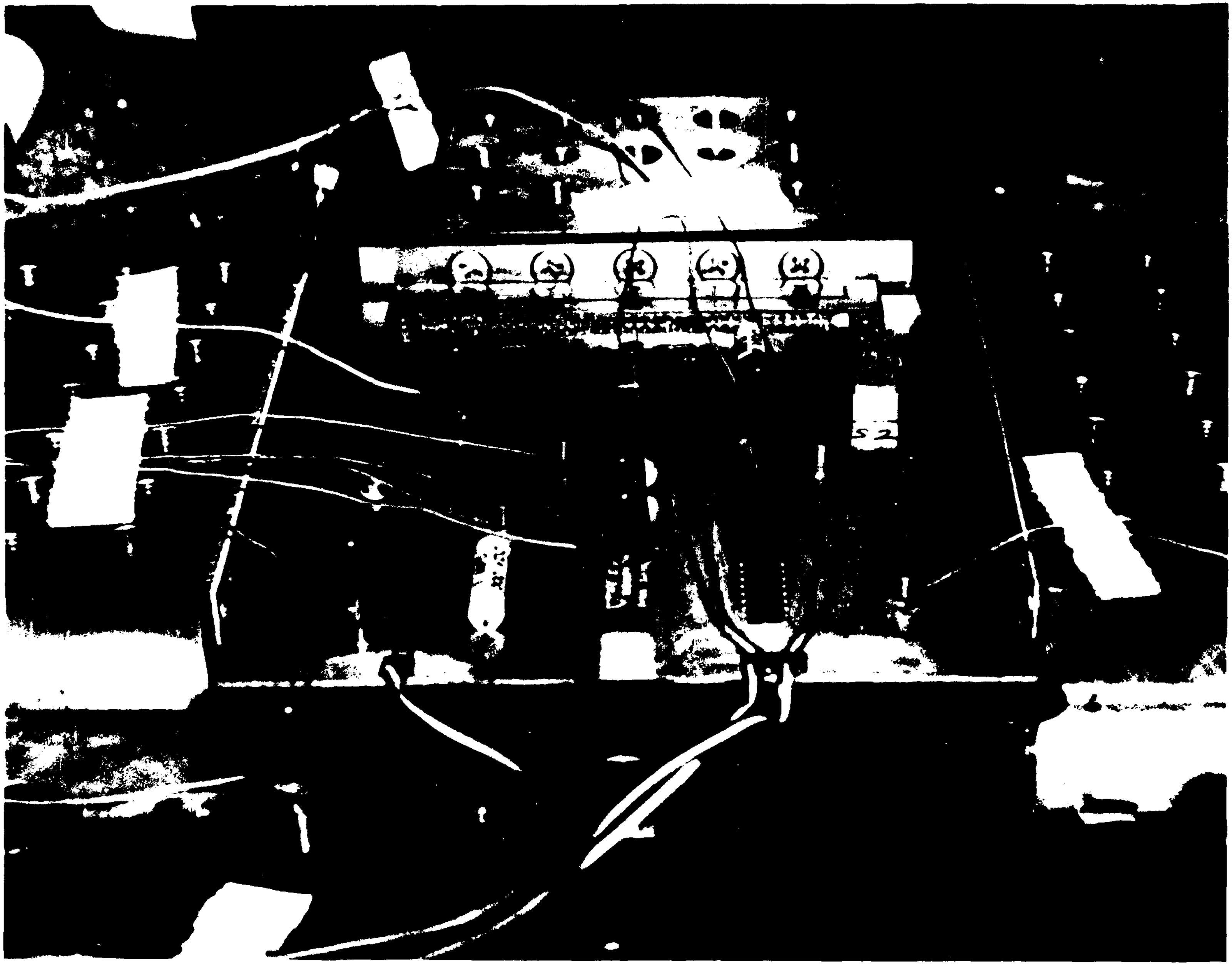
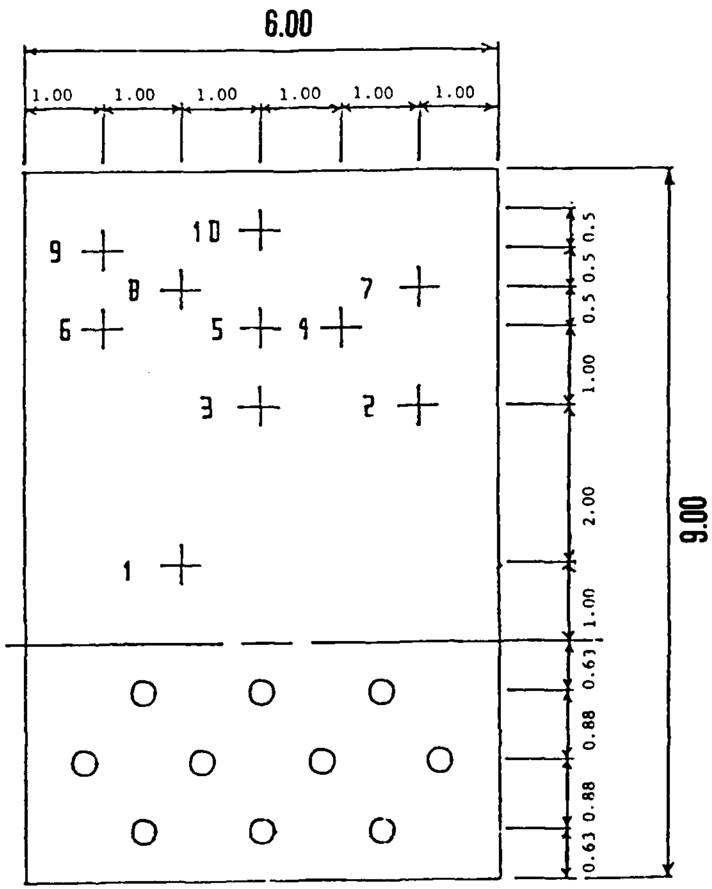
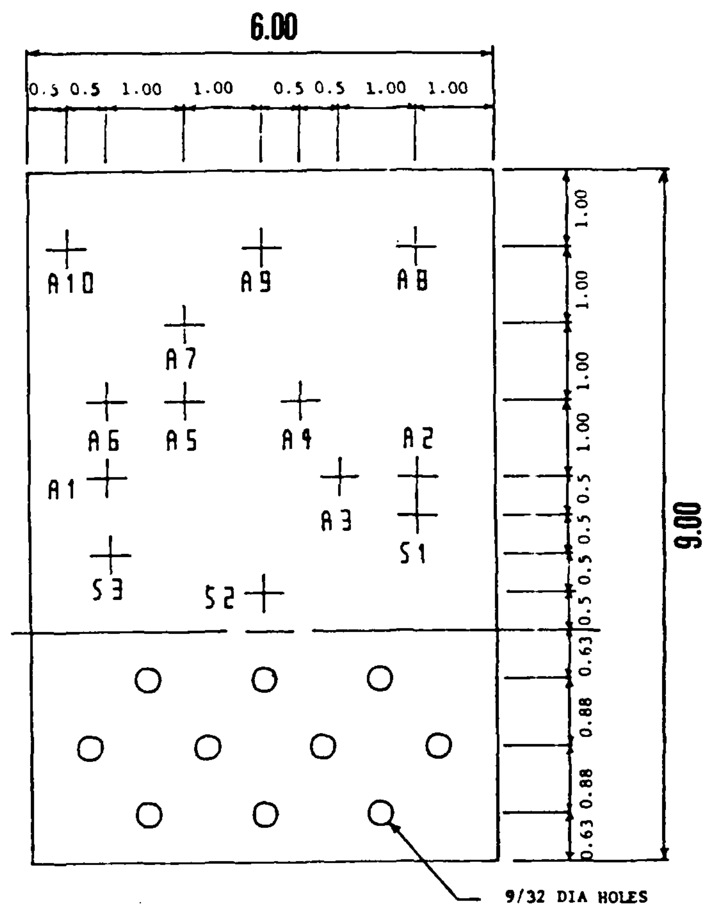


FIGURE 5 TEST SETUP FOR TWO EDGES SUPPORTED AND ONE EDGE FIXED BOUNDARY CONDITION

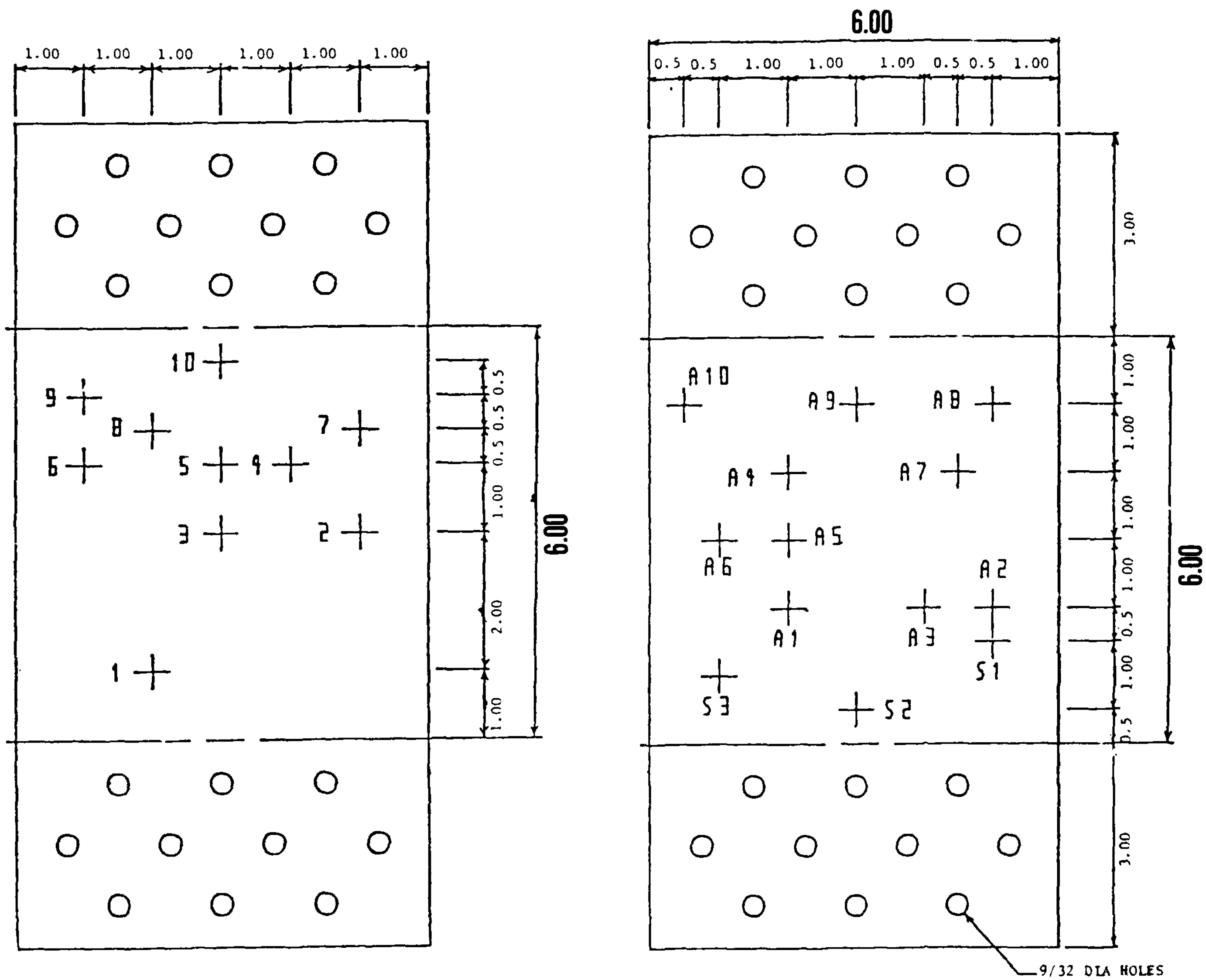


ACCELEROMETER LOCATIONS



COMPONENT LOCATIONS

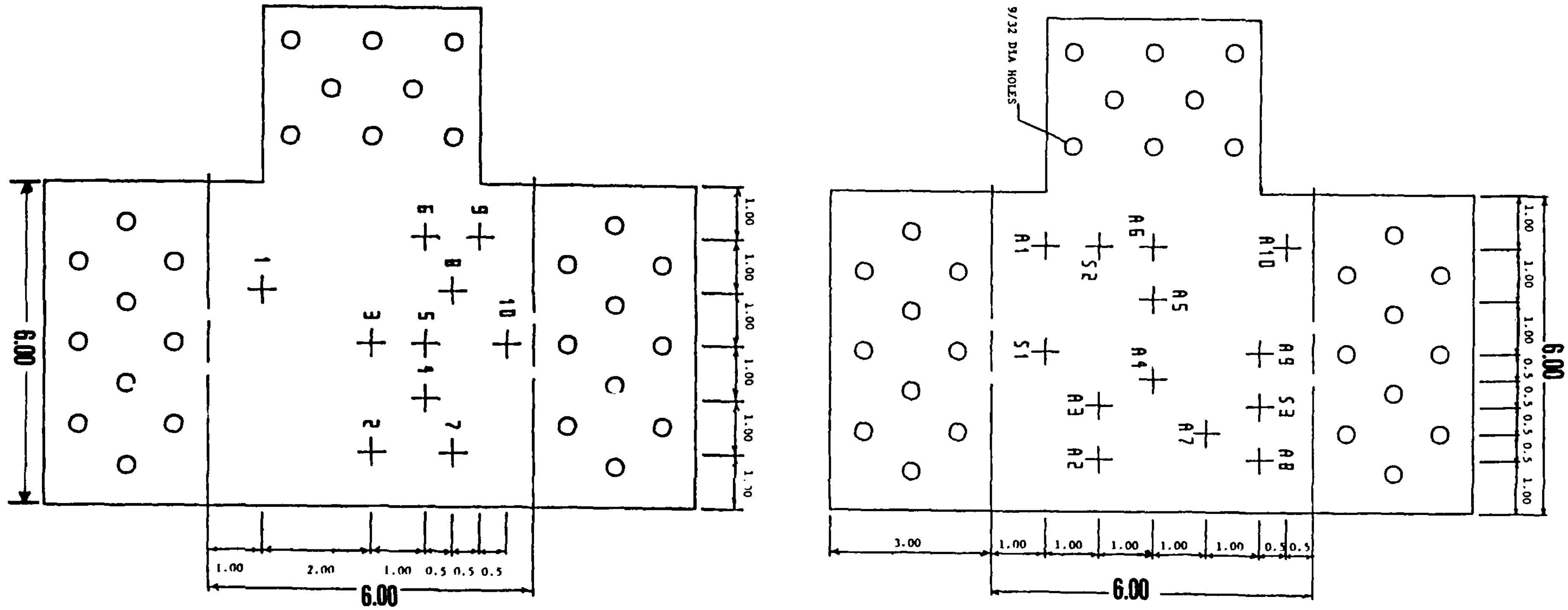
FIGURE 6 COPPERCLAD & STEEL PLATE (CANTILEVER) COMPONENT & ACCELEROMETER LOCATIONS



COMPONENT LOCATIONS

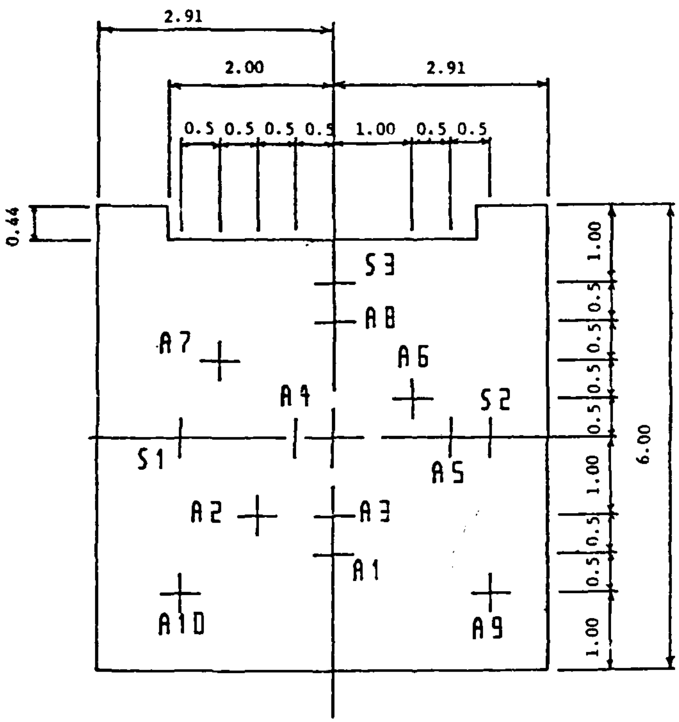
ACCELEROMETER LOCATIONS

FIGURE 7 COPPERCLAD & STEEL PLATE (TWO EDGES FIXED) COMPONENT & ACCELEROMETER LOCATIONS

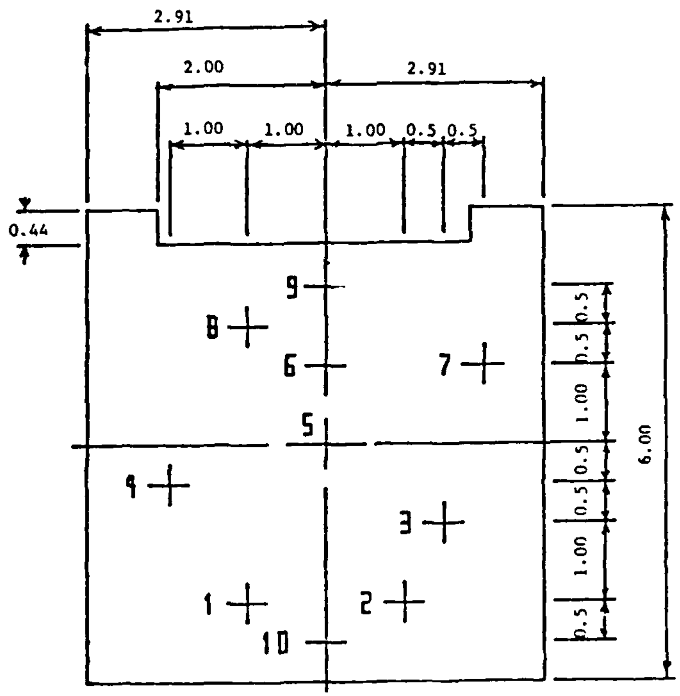


COMPONENT LOCATIONS **ACCELEROMETER LOCATIONS**

FIGURE 8 COPPERCLAD & STEEL PLATE (THREE EDGES FIXED) COMPONENT & ACCELEROMETER LOCATIONS



ACCELEROMETER LOCATIONS



COMPONENT LOCATIONS

FIGURE 9 COPPERCLAD PLATE (BURCHER GUIDE & CONNECTOR) COMPONENT & ACCELEROMETER

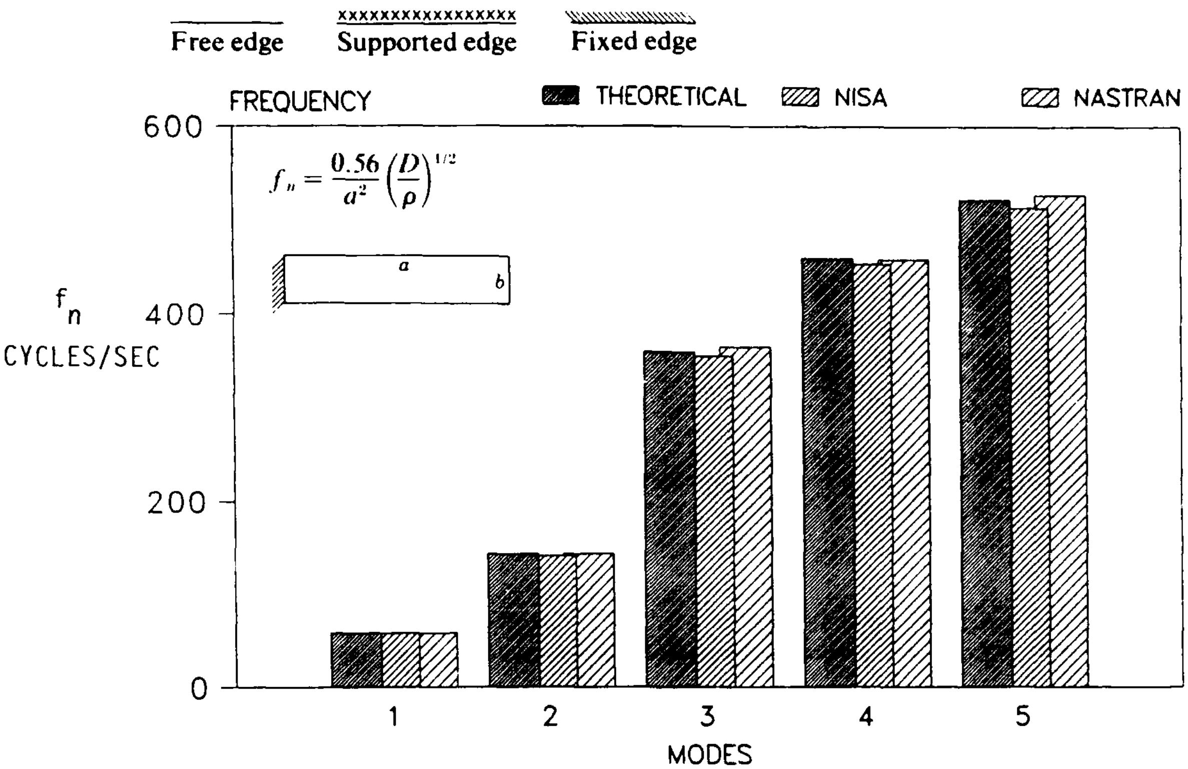


FIGURE 10 FREQUENCY CORRELATION (ONE EDGE FIXED)

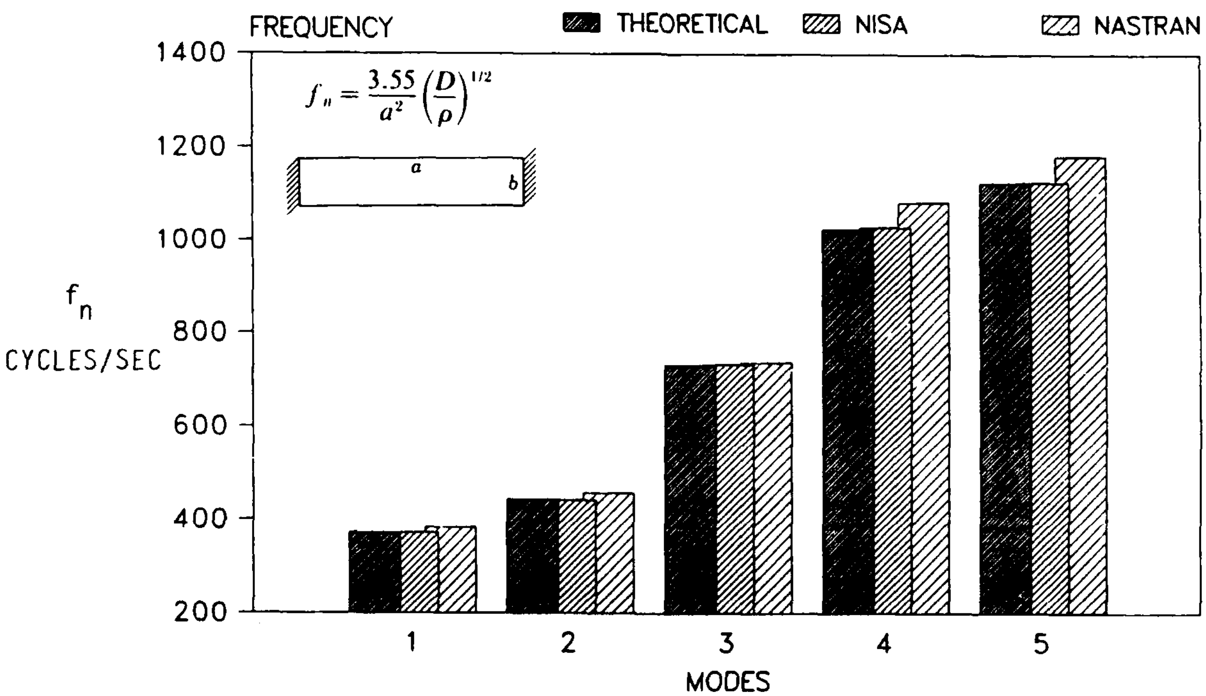


FIGURE 11 FREQUENCY CORRELATION (TWO EDGES FIXED)

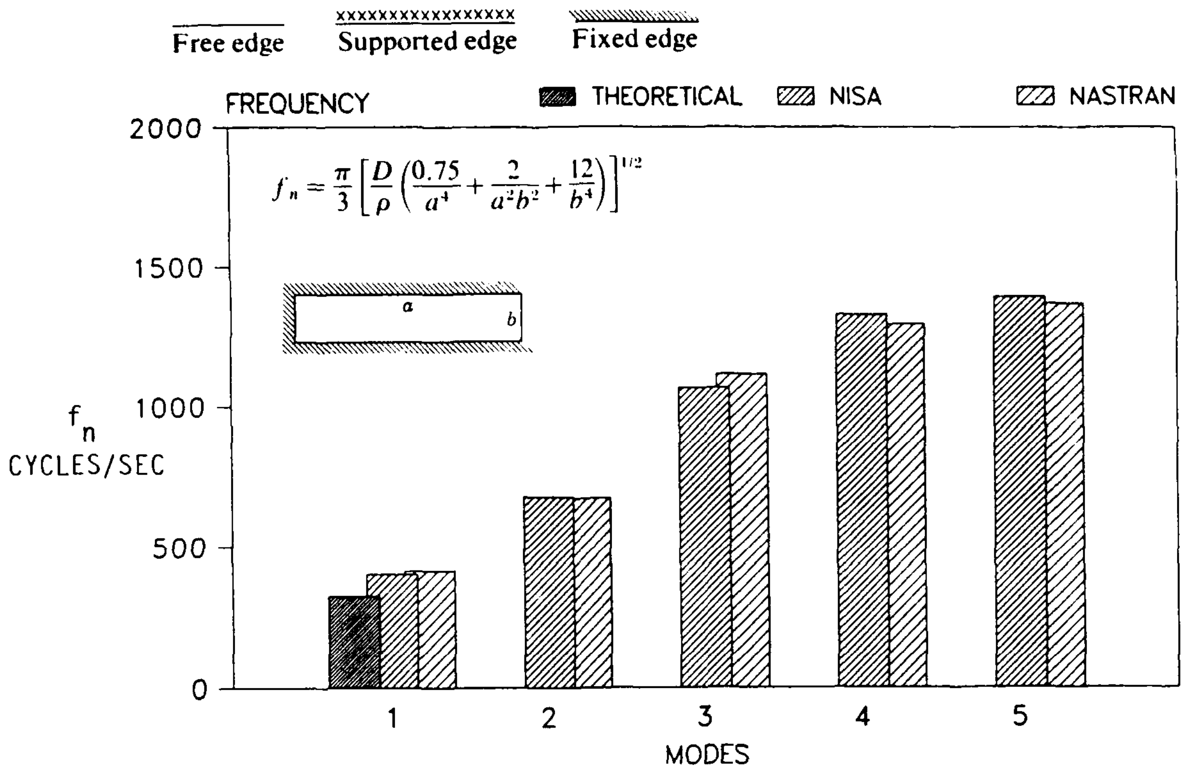


FIGURE 12 FREQUENCY CORRELATION (THREE EDGES FIXED)

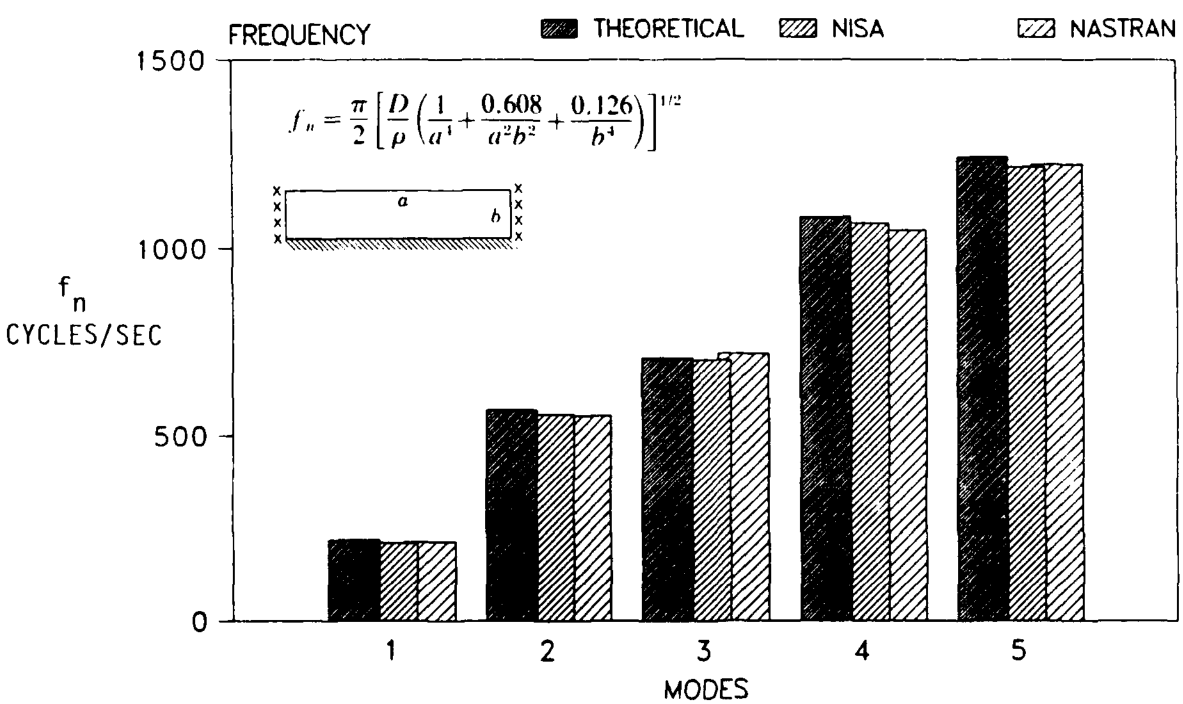


FIGURE 13 FREQUENCY CORRELATION (TWO EDGES SUPPORTED & ONE EDGE FIXED)

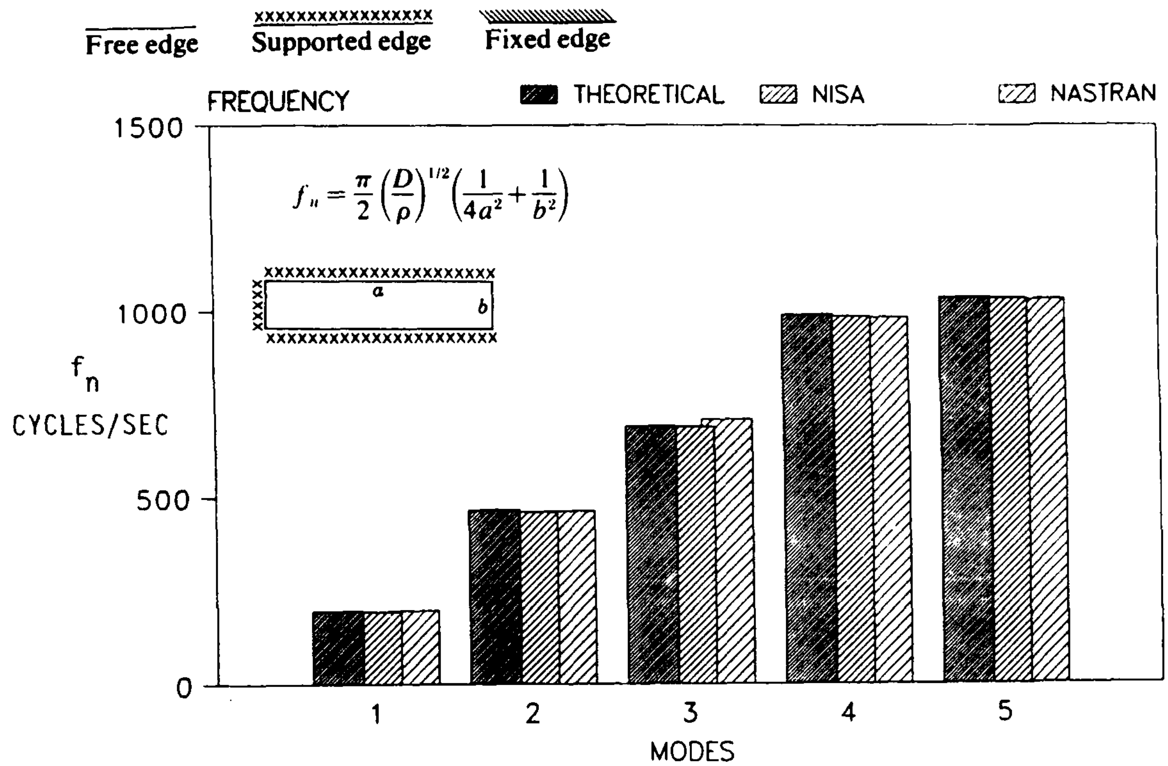


FIGURE 14 FREQUENCY CORRELATION (THREE SUPPORTED EDGES)

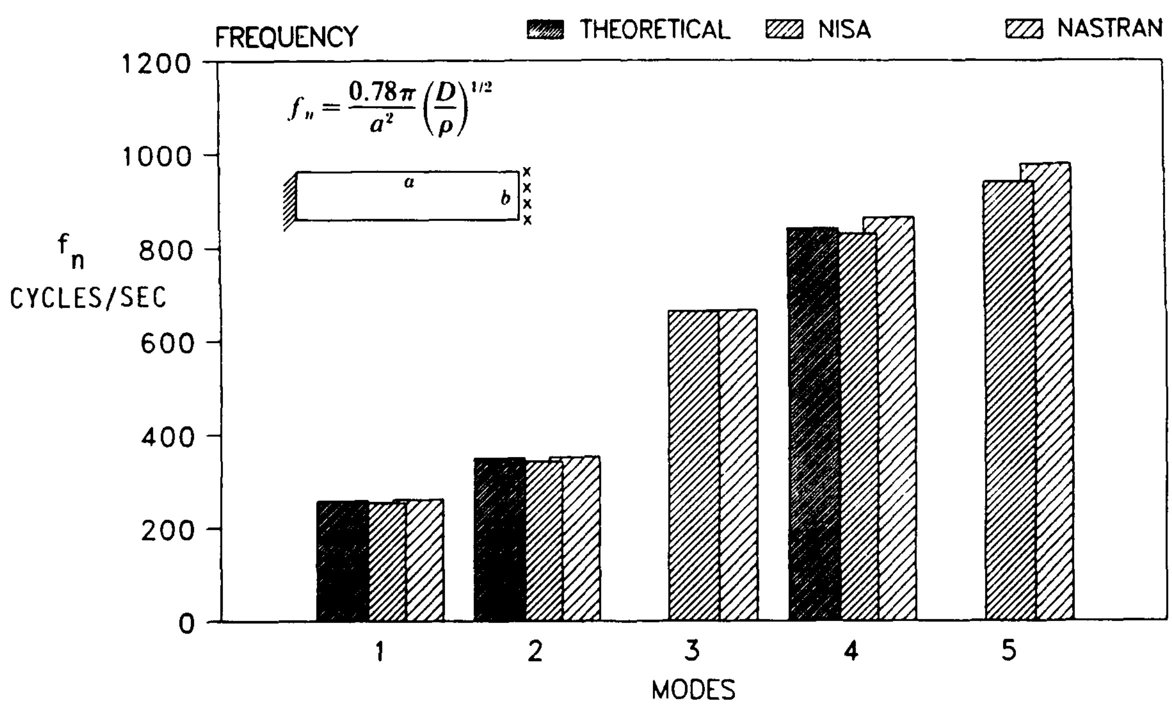


FIGURE 15 FREQUENCY CORRELATION (ONE EDGE SUPPORTED & ONE EDGE FIXED)

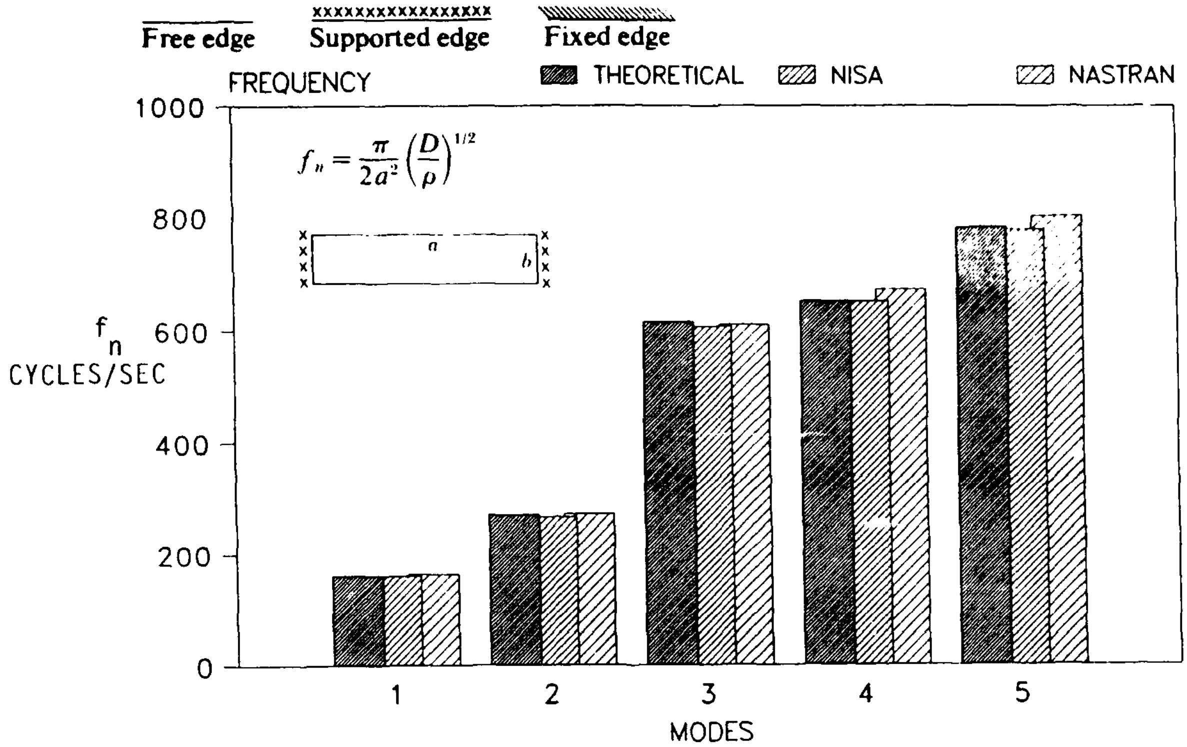


FIGURE 16 FREQUENCY CORRELATION (TWO EDGE SUPPORTED)

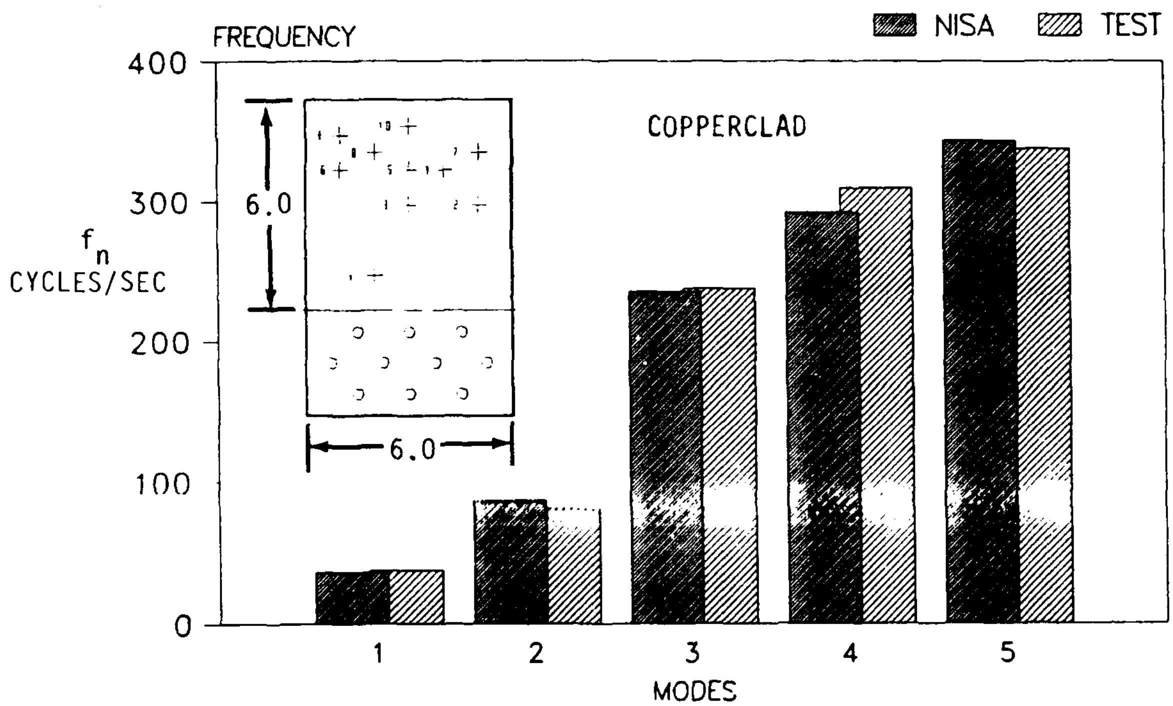


FIGURE 17 FREQUENCY CORRELATION (ONE EDGE CLAMPED - COPPERCLAD)

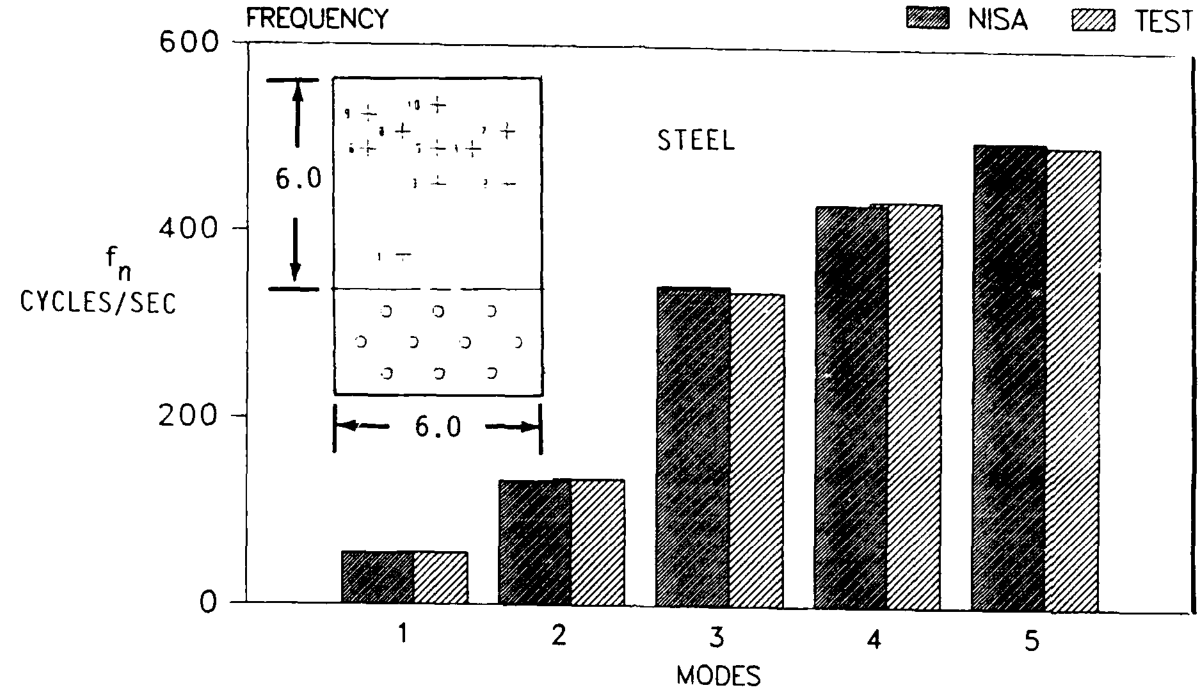


FIGURE 18 FREQUENCY CORRELATION (ONE EDGE CLAMPED - STEEL)

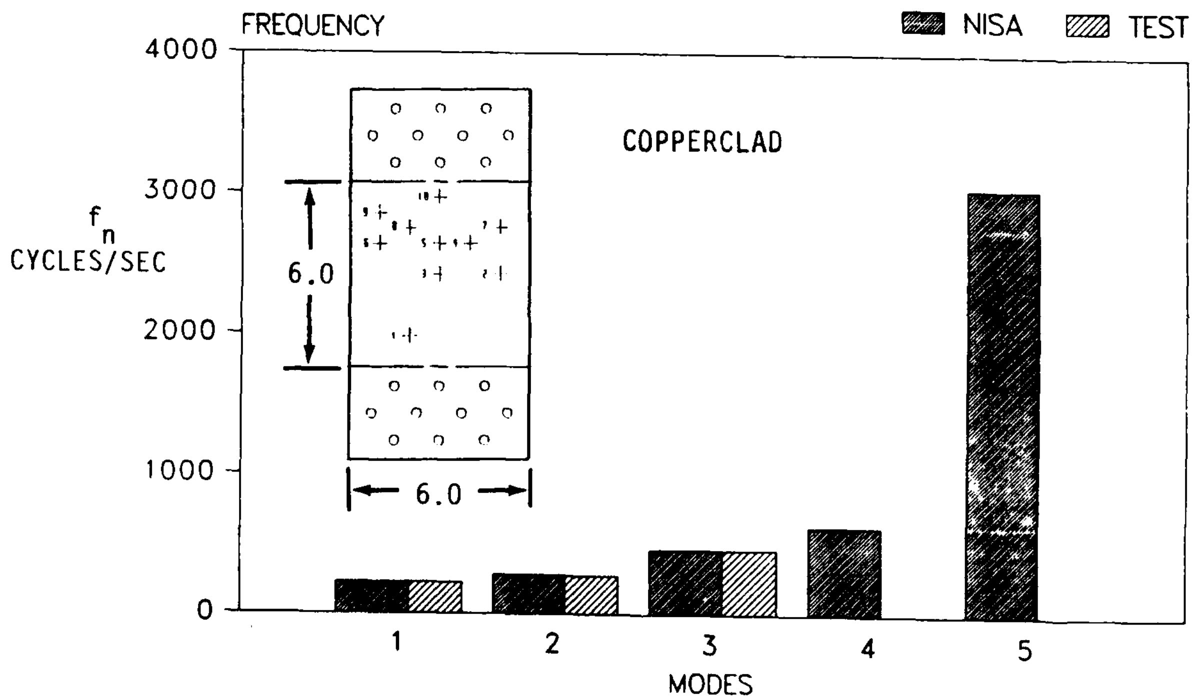


FIGURE 19 FREQUENCY CORRELATION (TWO EDGES CLAMPED - COPPERCLAD)

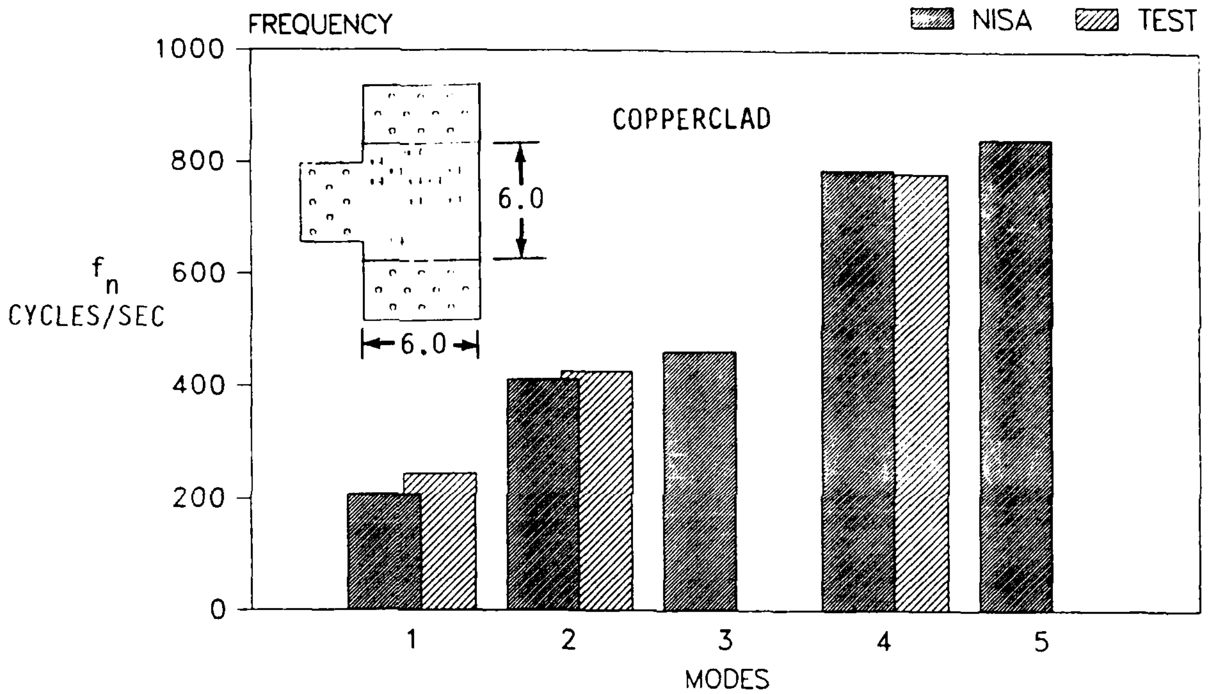


FIGURE 20 FREQUENCY CORRELATION (THREE EDGES CLAMPED - COPPERCLAD)

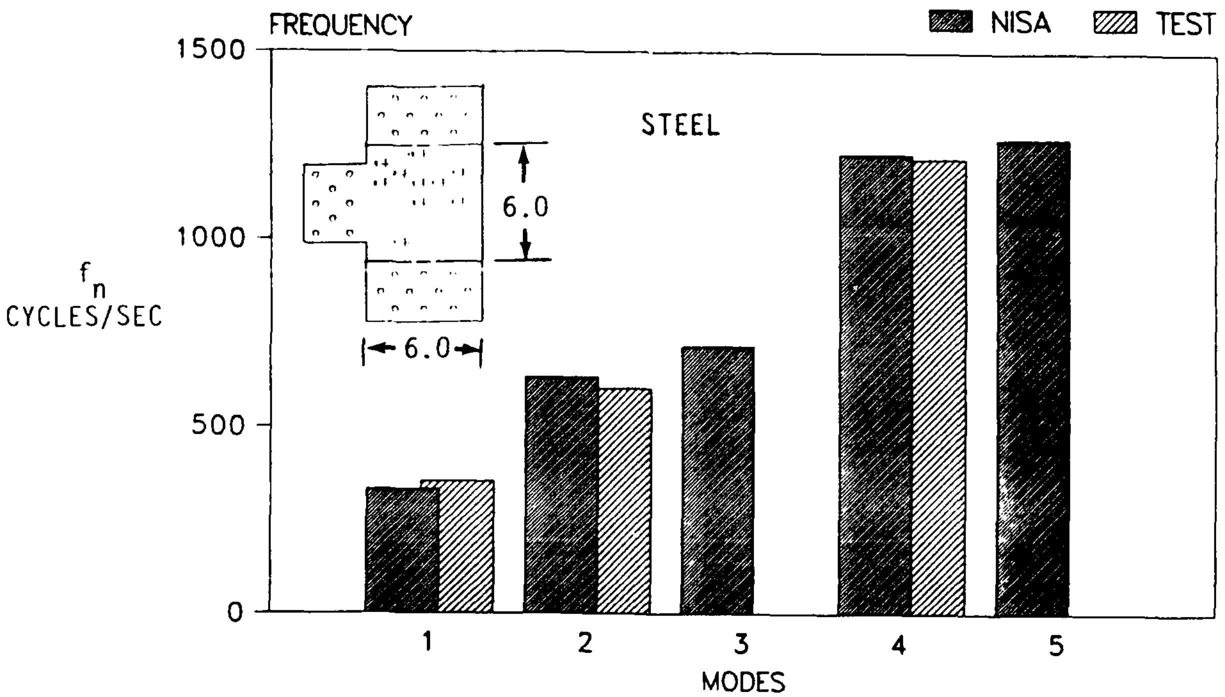


FIGURE 21 FREQUENCY CORRELATION (THREE EDGES CLAMPED - STEEL)

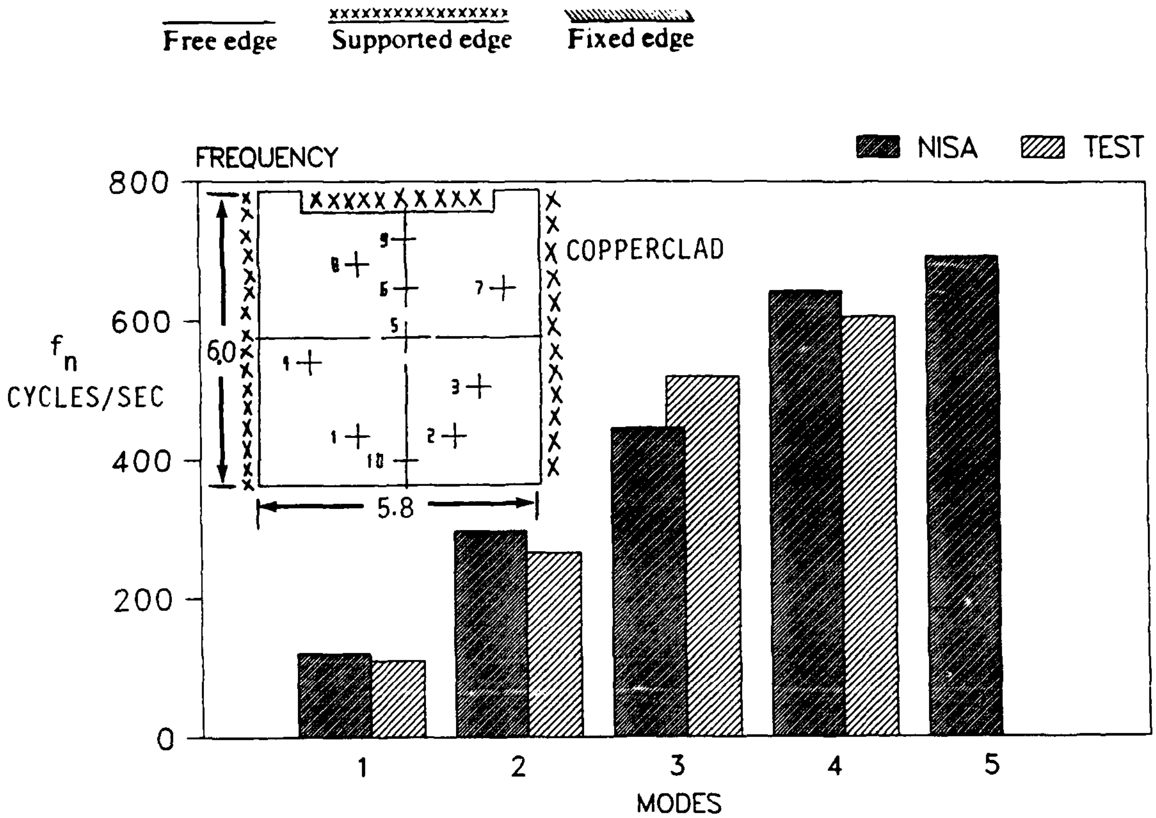


FIGURE 22 FREQUENCY CORRELATION (THREE EDGES SUPPORTED - COPPERCLAD)

☆U.S.Government Printing Office: 1990—748-056/24252